Development and application of a Cylindrical Active Tracker and Calorimeter system for Hyperon-proton scattering “CATCH”

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論　文　内　容　要　旨

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氏　　名	赤澤 雄也	提出年	平成　 30 年
学位論文の 題　　　目	Development and application of a Cylindrical Active Tracker and Calorimeter system for Hyperon-proton scattering “CATCH” (ハイペロン-陽子散乱実験に向けた円筒形飛跡検出器・カロリメータシステム“CATCH”の開発と利用)		

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A scattering experiment between a Σ hyperon and a proton is planned at J-PARC (J-PARC E40) in order to investigate the baryon-baryon interaction and to confirm the repulsive force due to the "quark Pauli effect", which causes the strong repulsive force by Pauli principle in the quark level and is considered as one of the origins of the repulsive core in the nuclear force. However, the quark Pauli effect has not been confirmed experimentally. In order to compare the experimental measured cross section of the Σp scattering with predicted ones from theoretical models with and without this effect, the accuracy of the measured differential cross section is required to be better than ±10% at 3 mb/sr.

In order to achieve the sufficient accuracy of the cross section, the high statistical data of identified Σp scattering events from background events is important. In order to overcome some experimental difficulties occurred in the past experiment, we proposed a new Σp scattering experiment. In order to use a high intensity π beam and to overcome the short life time of a Σ particle, I introduce a new identification method of the Σp scattering event, which does not need to detect Σ particles directly.
This experiment is performed with a setup of a new detector system called CATCH and two spectrometer systems installed at the upstream and at the downstream of a liquid hydrogen target. The momenta of π beam and scattered K^+ are measured by the spectrometers in order to reconstruct the momentum of a Σ beam produced via the $\pi p \rightarrow \Sigma K^+$ reactions. The scattering angle and the kinetic energy of recoil protons are measured by CATCH for the identification of the Σp scattering events.
This new method ("ΔE method") introduces "ΔE" defined as a difference between two values for the recoil proton's energy obtained by two different methods as following,

- Ep'_{calc} : A energy of the recoil proton kinematically calculated from the Σ beam energy and the Σp scattering angle,
- $Ep'_{measure}$: An actual measured energy of the recoil proton.

For the Σp scattering events, the ΔE ($=Ep'_{calc} - Ep'_{measure}$) distribution has a peak around zero. From the number of the peak counts, the scattering event is identified to derive the cross section. In order to realize the ΔE method, in addition to the spectrometer system, the recoil proton detector is necessary and required to measure the trajectory and the energy of the recoil proton. Since a high intensity π beam of 20 MHz is used in this experiment for the Σ production, a sufficient time response is also required for the detector. For this reason, I developed a new detector system, so called CATCH (Cylindrical Active Tracker and Calorimeter system for Hyperon-proton scattering).

CATCH is designed to have a large acceptance by covering the target cylindrically with a long sensitive area of 400 mm in the beam direction. CATCH consists of a Cylindrical Fiber Tracker (CFT) and a bismuth germanate (BGO) calorimeter. For the operation under a singles rate of 2 MHz in maximum for one CFT layer, the time resolution of CFT is required to be 2 ns (σ_{time}). In order to achieve the accuracy of ±10% in the Σp scattering cross section, the requirement for the resolution of ΔE is estimated to be better than 7 MeV from a simulation, which corresponds to the CFT angular resolution of 2 degrees (σ_θ) and the energy resolutions for BGO and CFT of 3%(σ_{EBGO}) at 80 MeV proton and 25% (σ_{ECFT}) , respectively. CFT is a tracking detector with a fast time response made of 5,000 scintillation fibers with a diameter of 0.75 mm. Each fiber signal is read by Multi-Pixel Photon Counter (MPPC, 1 × 1 mm^2, 400 pixels) fiber by fiber. In order to reconstruct tracks three dimensionally, two types of cylindrical layers were fabricated where fibers are placed with the straight and spiral configurations on the surface of the cylindrical layer, respectively. In the fabrication of CFT, it was difficult to place fibers at ideal positions exactly. The fiber positions were corrected with cosmic ray data. As for the BGO calorimeter, 24 BGO crystals are placed to surround CFT and are used to measure the kinetic energy of the recoil proton. The size of one crystal piece is 30×25×400 mm^3. After each detector was fabricated, CFT and the BGO calorimeter were combined together as CATCH.

In order to evaluate the performance of CATCH system for the first time, a pp and pC scattering experiment was performed at CYRIC (Tohoku University) in January 2017. A Polyethylene(CH_2) target of 800 μm thickness installed inside CATCH was irradiated by an 80 MeV proton beam, and scattered protons were measured by CATCH.

The angular resolution was evaluated to be 1.6 degrees (σ_θ) from the opening angle between two protons emitted from pp scattering. It satisfied the requirement of 2 degrees (σ_θ).

The energy calibrations of CFT and the BGO calorimeter were performed by using the relation between the energy of the scattered protons and the scattering angle measured by CFT. The energy resolution of the BGO calorimeter was obtained to be 1.5% (σ) for 80 MeV proton, and that of CFT was obtained to be better than 20% for the energy deposit of a proton in CFT (8 MeV – 20 MeV). As a result, the correlation between the scattered proton's energy and the scattering angle was consistent with the kinematic calculation.

For the identification of the scattering event, a ΔEp' (= Ep'_{calc} – $Ep'_{measure}$) is defined like the Σp scattering experiment. The ΔE resolution for the pC scattering was obtained to be about 2.3 MeV ($\sigma_{\Delta E}$). Since $\sigma_{\Delta E}$ depends on the beam energy and kinematics, the estimation for the Σp scattering experiment is necessary. Based on the obtained angular resolutions and the energy resolution of CFT and the BGO calorimeter, the ΔE resolution for the Σp scattering was estimated to be better than 5.5 MeV (σΔE) for all possible conditions. This value satisfies the requirement of 7 MeV (σΔE) to well discriminate the ΔE peak from background in the Σp scattering experiment.

The scattering differential cross sections of pp and pC scatterings derived with the CATCH system.

Data were taken with three different target positions to investigate the position dependence of the

CATCH performance. Only the relative cross sections could be derived due to a problem in the measurement of the absolute beam intensity. It was found that the angular distribution of the obtained relative differential cross sections were consistent with the reference results. The angular distribution of the pp scattering cross section is known to be flat in this energy and the angular region of θ_{CM}>30 degrees from the reference. In addition, the obtained pC scattering cross sections agreed with the past data at the scattering angles θ<35 degree, where the contamination by the inelastic scattering to the 4.4 MeV excited state of ^{12}C is negligible.

This difference between the measured result and the reference data is regarded as a systematic error in the cross section, which was found to be within ±10%. It satisfies the requirement for the Σp scattering experiment of ±10%. These results suggested that I have established an analysis method for deriving the cross section for the newly developed CATCH system.

In conclusion the CATCH system was fabricated and the test experiment was performed for the first time. The analysis method for deriving the cross section with the CATCH system was also established for the first time. As the results of the performance evaluation, the angular resolution of CFT was obtained to be 1.6 degrees (σ_θ), and the time resolution of CFT was obtained to be 1.8 ns (σ_{time}). The ΔE resolution in the Σp scattering was estimated to be better than 5.5 MeV ($\sigma_{\Delta E}$) even for the maximum Σ beam energy of 150 MeV. The systematic error in the cross section is within ±10%.　Therefore, I have confirmed that the CATCH system has sufficient performances for the Σp scattering experiment at J-PARC to compare with the theoretical models and to determine the quantitatively strength of the repulsive force. It is also expected to provide the information of the Σ^-p interaction for the study of the interaction between baryons.

別　紙

論文審査の結果の要旨

本論文は、J-PARC で実施予定のΣ粒子と陽子との散乱実験のために必要となる新型の反跳陽子検出器を開発、製作し、ビームを用いたテスト実験を行ってその性能を実測し、検出器が J-PARC の本実験で必要となる性能を満たしていることを示したものである。

中間子交換の描像では理解できない核力の斥力芯をクォーク描像で理解するため、Σ粒子と陽子の相互作用を散乱実験によって詳しく調べる研究が計画されている。この実験では、従来のΣ・陽子散乱実験の問題点を解決するために考案された新しい実験手法（液体水素標的を用い、Σ粒子の運動量をイベントごとに生成反応から測定し、反跳陽子の角度とエネルギーを測定して両者の整合性から散乱事象を同定する方法）を用いて、大立体角と高い時間分解能をもった検出器によって、大強度πビームを用いてΣ粒子・陽子散乱実験を画期的な高統計精度で実施することを目指している。この実験を実現するため、赤澤氏は、それぞれに MPPC 光センサーを取り付けた約 6000 本のシンチレーションファイバーを用いた多円筒型飛跡検出器と、その外側を囲む BGO カロリメータとを組み合わせた検出器群 CATCH を設計・製作した。この製作は、赤澤氏が主導して、さまざまな工夫を重ねることで実現したものである。

さらに赤澤氏は、宇宙線によってファイバー位置の較正を行ったのち、CATCH の性能を確認するため、東北大サイクロトロンを用いて、80 MeV 陽子ビームと陽子または炭素原子核との散乱における反跳陽子を CATCH で測定した。その結果、反跳陽子の角度分解能とエネルギー分解能は要求性能を十分にみたし、散乱事象同定のためのエネルギーの整合性の測定精度は目標である 7 MeV 以下を達成していることが示されて、CATCH がΣ・陽子散乱本実験のために必要な性能を十分に満たしていることが判明した。さらに、赤澤氏はデータおよびシミュレーションから CATCH の検出効率を求め、陽子・陽子、陽子・炭素散乱の断面積の相対角分布を求め、過去に測定された角分布と 10%以内の精度で一致することを示した。こうして、J-PARC での本実験ではこの検出器群によって予想通りの高精度（誤差 10%）のΣ・陽子散乱断面積データが測れることを示した。このような大規模・多チャンネルの新型検出器を開発・製作するとともに、ビームを用いて詳細な性能評価を行った成果は、大変高く評価できる。

本論文は、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，赤澤雄也提出の博士論文は，博士（理学）の学位論 文として合格と認める。